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# *Simulating Mother–Child Interaction: Exploring Two Varieties of a Non-linear Dynamic Systems Approach*[1]

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**In theoretical analyses of early mother–child interaction, it has been argued that interaction should be studied in its flow over time, and that the behaviour of each interactant is likely to be non-linearly determined. The mother–child dyad can be seen as a non-linear dynamic system, the development of which is determined by the mutual relations between its elements. The present study is based on the idea that computer simulations can be used to find out what kind of empirical implication these ideas have. Accordingly, we describe two non-linear dynamic systems-based models for simulating mother–child interaction, i.e. a connectionist network model and a logistic growth model. Three determinants of the nature of the interaction, i.e. the child's irritability, the mother's sensitive responsiveness, and the intensity of an external stressor bothering the child, are varied systematically. Although the results of both simulations differed considerably, they shared the fact that small changes in stressor intensity produced abrupt changes from one type of interaction to another. In addition, increasing stressor intensity sometimes had the paradoxical effect of resulting in less, rather than more, distress on the side of the child. Though irritability and responsiveness were varied in a less fine-grained way than stressor intensity, the results suggest that similarly small differences in these dimensions at different parts of the dimension's scale range have differentially strong effects on the nature of the interaction. It is concluded that these simulations help us to specify the nature of empirically researchable phenomena that are to be expected, given the assumptions listed above. Further elaboration of the models and comparison with longitudinal empirical data is needed to answer further theoretical and practical questions. Copyright © 2000 John Wiley & Sons, Ltd.**

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Because early mother–infant interaction is assumed to be very important for the development of the child, much research has been directed towards identifying the characteristics of mothers or infants that effect either the nature of their interaction, or the infants' later development, or both. Unfortunately, it has been very difficult to demonstrate strong relations between the presence of specific characteristics of mother and child on the one hand, and the nature of the interaction and/or later developmental outcomes on the other hand. Research outcomes have been contradictory, and even when theoretically expected relations were found, they were not so strong as they should be according to theory (cf Crockenberg and Smith, 1982; Peters-Martin and Wachs, 1984; Hubbard and Van Ijzendoorn, 1991). The general aim of the present study is to contribute to a better understanding of the link between characteristics of mother and child, and the nature of their interaction. Two possible causes of the relative lack of strong empirical findings have been suggested in the literature. The first concerns the conception of interaction that underlies existing research, and the second concerns our conception of how interacting individuals affect each other.

With respect to the first point, theorists have argued that the link between characteristics of mother and child and the nature of the interaction should not be conceived of as a simple pattern of cause and effect such as 'characteristic A causes interaction type B' and 'characteristic C causes interaction type D'. Rather, the nature of the interaction is assumed to depend on what Lerner (1982) and Fogel (1993) have called the 'fit' between mother and infant behaviour. A key element of this view is that interaction cannot be seen as the exchange of messages between two stable entities (Fogel, 1993). As early as 1974, Lewis and Lee-Painter made a similar point by stating that analysis of interaction should focus on the interaction, and not on the separate behaviours or characteristics of the participants in the interaction (Lewis and Lee-Painter, 1974). The behaviours are created in the interaction, in that they depend on the interactant's own previous behaviours and of the other interactant's previous behaviours (De Weerth, 1998).

This conception implies that interaction should not be studied by using scores representing how often particular behaviours occurred during an observation period, as is frequently done in interaction research, but by focusing on the dynamic quality of the interactions, that is, on their flow with time. The analysis should focus on the interaction itself, rather than on the elements.

A second potential cause of the relative lack of strong links between child and parent characteristics and the nature of their interaction and children's developmental outcomes might be that researchers have traditionally assumed such relationships to be linear. For example, empirical analyses of the relations between mothers' sensitive responsiveness and children's irritability on the one hand, and the nature of mother–child interaction on the other hand, have usually been based on linear statistical models (see, for example, Crockenberg and Smith, 1982; Peters-Martin and Wachs, 1984; Hubbard and Van Ijzendoorn, 1991). Accordingly, the possibility that the relationships to be investigated might be non-linear has largely been ignored.

This is unfortunate, because present-day theorists increasingly recognize that the relation between each participant's behaviour and its determinants is unlikely to be a simple linear one. In living systems s-shaped fuctions, critical values, and U-shaped relations are far more common than linear functions. This implies that two interacting individuals can be seen as a non-linear dynamic system, the development of which is determined by the mutual relations between its elements.

Both the idea that interaction should be studied in its flow over time, and the idea that the behaviour of each interactant might be non-linearly determined, have made the task of interaction researchers a more difficult one. It is no longer obvious what kind of data should be gathered and what kind of phenomena should be studied in interaction research. Although the limitations of traditional sumscore-based measures have become clear, how to replace them is not so evident. However, in the next section, we will discuss the type of research that may help to identify potentially interesting phenomena.

## SIMULATING NON-LINEAR SYSTEMS

In a non-linear dynamic system, similar changes in one element of the system can have quite different effects on the state of the system, depending on the state of the system as a whole. Accordingly, if one conceives an interacting dyad as a non-linear dynamic system, one thing to study is how continuous changes in the values of theoretically relevant variables affect the nature of the interaction in the dyad. For mother–child interaction, one might think of changes in the child's sensitivity to bothersome circumstances, or the mother's sensitivity to the child's needs, or the presence of stressful circumstances. Obviously, this is not easy to investigate in real life mother–child dyads, because it is very difficult to manipulate experimentally the relevant variables with a sufficient degree of precision.

The present study is based on the idea that computer simulations might help in the task of finding out what kind of empirical phenomena are to be expected, given the assumptions about the nature of interaction and about the possible non-linearity of the interactants' reactions that we described above. One reason for this is that in simulations the flow of the simulated interactions over time can be studied easily. A second reason is that any theoretically relevant variable can easily be manipulated experimentally. Finally, a third reason is that the present-day simulation literature offers several approaches that are based on non-linear dynamic systems theory, thus enabling us to honour the idea that the interactants' behaviour might depend non-linearly on its determinants.

Based on the above ideas, the aim of the present study is to explore the issue of what kind of empirical phenomena are implied in the theoretical notion that the behaviours of an interacting mother and child are non-linearly dependent on their individual characteristics and on external conditions. Given this very general aim, it would be unwise to focus on one non-linear dynamic systems model in particular. It would be unclear which aspects of the results should be seen as resulting from the non-linearity of the model, and which aspects should be seen as resulting from particular characteristics of the model that other non-linear approaches do not share. Accordingly, we need two different non-linear dynamic systems-based computer simulation models, both of which should be well suited to model both the interaction between two individuals, and the changes in their interaction over time.

We identified two such models, both of which have the additional advantage of having been applied in developmental psychology before.

 

The first is a connectionist model of the type made popular in psychology by McClelland and Rumelhart (McClelland *et al*., 1986; Rumelhart *et al*., 1986). The model has generated ambitious theorizing and research in many areas, including developmental psychology (Elman *et al*., 1996). Until now, most developmental applications have been in the fields of cognitive and language development. Nevertheless, the model has already been used to study adult social interaction (Hutchins, 1991), and it has been argued that the approach should be extended to the field of social development as well (Elman *et al*., 1996, p. 394).

The second model is a logistic growth model of the type that Van Geert (1991, 1994) has introduced to developmental psychology. Van Geert and his colleagues have elaborated dynamic systems models in such diverse fields as cognitive development (Van Geert, 1991), language development (Ruhland, 1998), the development of meaning making (Kunnen and Bosma, 1996), and the developmental theories of Piaget and Vygotsky (Van Geert, 1998).

Both types of models have been applied successfully to describe changes in psychological systems consisting of interactants behaving non-linearly, and both are well suited to describe such development as the result of an iterative process. Accordingly, both the connectionist network and the dynamic growth model seem suitable for the task of spelling out the empirical implications of the theoretical assumptions that were described above. To the extent that both types of simulations yield similar results, they can safely be taken to represent the general implications of using a non-linear dynamic systems approach to studying interaction.

It should be noted that the aim of this study, unlike many other studies using mathematical modelling, is theoretical clarification. Our aim is not to develop a ready-for-use model that covers all or even the most important aspects of mother–child interaction, and neither do we aim to build a model that fits any known data set. Instead, we aim to show how dynamic models can be applied in elaborating our knowledge of interactional processes. Of course, elaborate versions of the models that we propose in this paper should ultimately fit empirical data concerning mother–child interaction. At this moment, however, empirical data of the type that is needed to test dynamic models do not exist. Such data might become available when empirical researchers become increasingly aware of the nature of the phenomena that should be looked for when taking a non-linear perspective on interaction processes. It is our hope that the present study will stimulate this awareness, and that data will become available that can be used to test models like the ones we propose in this paper.

## THEORETICAL ASSUMPTIONS BEHIND BOTH MODELS

Based on the ideas already stated, we will use both the connectionist and logistic growth types of models to simulate the interaction between a mother and a young child, who is assumed to experience discomfort as a result of an irremediable external stressor. One might think of a child who has got tired to a certain extent or, alternatively, of a child who feels a certain degree of pain. We chose to focus on this type of interaction because it enables us to study how the nature of the interaction changes as a function of variation along three different dimensions, i.e. the intensity of the external stressor, the child's sensitivity to the stressor, which is further referred to as *irritability*, and the mother's sensitivity to the needs of the child, which is further referred to as *sensitive responsiveness*.

 

In the present study, the latter two dimensions will only be used to create several artificial mother–child dyads, each of which is exposed to continuously increasing levels of stressor intensity. We decided to focus on the effects of continuously increasing stressor intensity, rather than on the corresponding effects of irritability and sensitive responsiveness, because such an approach is most likely to have a close empirical analogue. For example, if one equates the stressor intensity dimension with something like a child's tiredness that increases over the course of a day, an empirical analogue of our simulation approach would consist of studying mother–child interaction over the course of 1 entire day in dyads consisting of several differentially responsive mothers and several differentially irritable children.

To build a simulation model of any psychological process assumptions concerning the nature of this process, referred to by Van Geert (1994) as the psychological model, they have to be translated into the language of the model. As our models are aimed to simulate short-term mother–child interaction in stressful situations, the models describe the changes over time in the behaviour of both mother and child. Children's distress behaviour is described on a continuum from being quiet and asleep, to crying extremely loudly and showing signs of severe distress, such as kicking (Gustafson and Harris, 1990). Maternal behaviour is also described as a continuum, running from being passive, to general soothing behaviour, to active searching and trying to remove any causes of the distress. The psychological model consists of assumptions about the variables that are important in the real time interaction between mother and infant, and about how these variables affect each other. Basically, the interaction is described as an iterative process in which both interactants mutually affect each other. Our assumptions are the following:

1. When an external stressor is active, a child's distress responses will be elicited. However, children differ in terms of the impact that the stressor has on their responses, that is, they differ in terms of irritability.
2. A child's distress responses will generally activate the mother. She will adjust her activity to the behaviour of the child in order to quieten the child. Gustafson and Harris (1990) suggested a rather general pattern of maternal reactions to infant crying. That is, mothers will usually start with general soothing in cases of minor distress (vestibular stimulation, talking, picking up the child and tactile stimulation). If the child's distress nevertheless increases, mothers will look for specific causes of the distress, for example by checking the nappy and feeding the child.
3. Mothers differ in terms of their reactions to the same type of child behaviour, that is, in terms of the readiness and accuracy by which they react in an appropriate way to the child's signals (e.g. Grossmann *et al*., 1985; Hubbard and Van Ijzendoorn, 1991). Although mothers are generally able to discriminate between 'undefined' crying and crying for a specific cause like hunger, and in some cases also between infants' signals of hunger versus pain, there are considerable interindividual differences in this ability to differentiate (Gustafson and Harris, 1990).
4. The child will generally be quietened by the mother's behaviour, if this behaviour is well adjusted to the child's needs (Papousek, in press). For example, the mother can stop minor distress, as shown by quiet crying of the child, if she reacts contingently with soothing.

We will subsequently point out the way we actually implement these assumptions in our models. Because of the mutually non-linear relations between the interactants' behaviour, predicting in advance how each specific dyad will react to the increasing stressor intensity is impossible. We do predict, however, that both models will produce at least some dyads in which the mother's intervention affects the child's distress response at low levels of stressor intensity, but not at high levels of stressor intensity. Moreover, we expect the change between both regimes to be a non-linear one in such dyads.

## STUDY ONE. THE CONNECTIONIST NETWORK SIMULATION

The workings of connectionist networks are in some respects similar to what we know about the workings of real-life nervous systems. That is, connectionist networks consist of several interconnected units that can be considered artificial 'neurons', in that they can activate and inhibit each other. The network is connected to the external world, in that at least some units can receive input from outside, and at least some other units can give output and in doing so affect the external world. An important feature of currently used connectionist networks is that each unit reacts to the input that it receives according to a non-linear function.

Connectionist networks became popular in psychology when learning algorithms were discovered that enabled researchers to construct networks capable of learning from experience (McClelland *et al.*, 1986; Rumelhart *et al.*, 1986). This feature enables researchers to study the learning curves of such networks, but it can also be used for a different aim, i.e. to construct networks that behave in particular desired ways. In this study, we used the ability of the network to learn to construct the particular networks needed for this simulation.

The simulation reported in this paper is an extended and improved version of a simulation that one of us carried out previously, and that was briefly described by Olthof (1997). A connectionist network was constructed so that it behaved as a child who experiences discomfort when it is bothered by one of two different external stressors. We will further call this network KidNet. We constructed a second network (MomNet) so that it behaved as a mother who is trying to comfort the child. The construction of these networks was based on the assumptions described above. To simulate mother–child interaction, KidNet and MomNet were connected to each other so that the one network's output served as the other network's input and *vice versa*.

### *Method*

Using McClelland and Rumelhart's (1988) BP programme, we constructed two types of three-layer back-propagation networks to serve as KidNets and MomNets. We constructed networks in such a way that the output of a KidNet could serve as a MomNet's input and *vice versa* (see Figure 1). Conceptually, KidNets consisted of four input units, two hidden units and two output units (technically, there were another two input units, which will subsequently be described).

We designed two of the input units to receive stimulation from the non-interactive outside world. This stimulation is taken to represent two different types of external stressors, each of which would cause discomfort in a real-life child. Therefore, we will further refer to these units as the KidNet's *stress-sensitive* input units. We designed the two other input units to be connected to the output units of the MomNet with which the KidNet would be interacting.

That is, when simulating interaction, MomNet's output activated these units, and we will further refer to them as the KidNet's *social* input units. The MomNets had an identical architecture, except that no input units were connected to the outside world, that is, MomNets had only two social input units activated by the output units of the KidNet with which they were interacting.

We wanted to ensure that the responses of the network would not only reflect the currently available input from their interaction partner (and, in the case of KidNet, from the external stressors), but also the nature of the interaction at previous points in time. For this, we used an architecture introduced by Jordan (1986) and successfully used by Elman (1990). For this purpose, both types of networks were made sensitive for temporal sequences by adding two additional input units (further referred to as *context units)*, which received as their stimulation the activation of the network's hidden units in the previous cycle. This causes the network's output to be affected not only by the current input, but also by the input in previous cycles. Effectively, the context units serve as a dynamic memory that enables the network to let its output depend not only on the current state of affairs, but also on previous states of affairs.

Without taking any further measures, the behaviour of networks like those described above is subject to only very global constraints that are inherent to the architecture of the networks (Elman *et al.*, 1996). However, to be able to use these networks for simulating mother–child interaction, their behaviour should be subject to much stronger constraints. That is, like a real-world child, KidNet should have a natural tendency to produce a distress response when bothered by some external stressor and, like a real-world mother, MomNet should try to provide comfort to her KidNet. Furthermore, like real-world children, KidNets should differ in terms of how sensitive they are to an external stressor. MomNets should differ as to how responsive they are to their KidNet's distress responses.

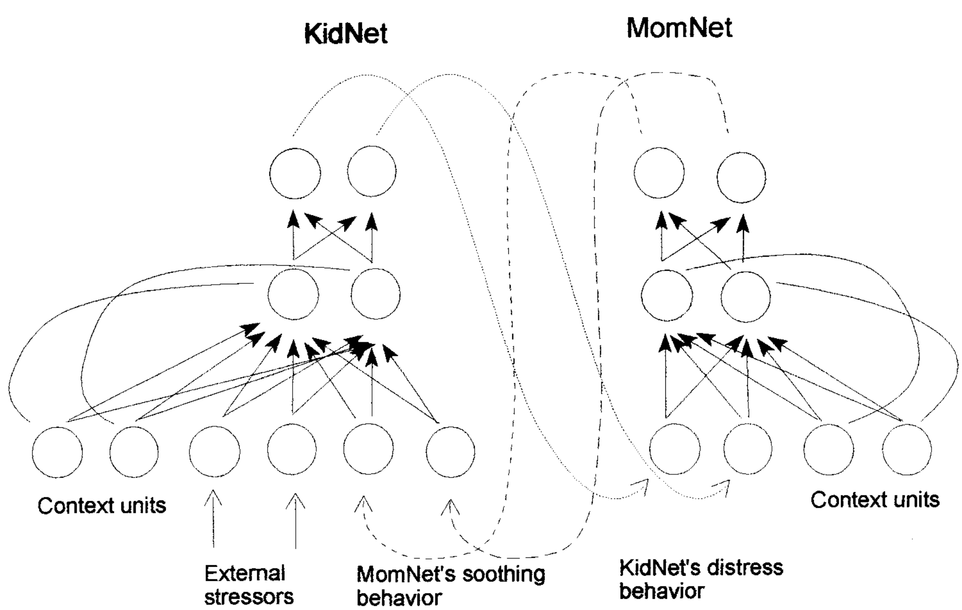


Figure 1. The pattern of connectivity of the networks that were used.

To construct networks in which behaviour is subject to these constraints, we used the ability of the network to learn, that is, both the KidNet and MomNet networks were subjected to a training regime designed to produce the desired behavioural tendencies. By varying the exact nature of the training regime, we were also able to construct eight different KidNets that differed in terms of their irritability, and eight different MomNets that differed in how responsive they would be to KidNet's distress responses. The exact way in which these networks were constructed and combined into 64 different KidNet–MomNet dyads is described in detail in Appendices A, B and C.

The actual interaction simulation within each of the 64 dyads was carried out by subsequentially activating each KidNet's stress-sensitive input units with each of 50 levels of externally caused stress. Stressor intensity varied from extremely low to very high. For each level of stressor intensity, the dyads interacted during a time period consisting of 50 iterations. This scheme allowed us to examine how the nature of the interaction within each KidNet–MomNet dyad would be affected by increasingly intense pressure from the external stressors. The technical details of running the interaction simulation are described in Appendix D.

### *Results and discussion*

Running the simulation yielded two (stressors) *64 (KidNet–MomNet dyads) *50 (stressor intensity levels) = 6400 interaction sequences. Space is obviously lacking to present these sequences here, but to enhance understanding of the material that will be presented later on in this paper, two of them are presented in Figure 2 for illustrative purposes.

The upper panel of Figure 2 depicts the responses of a moderately irritable KidNet and a moderately responsive MomNet, who are interacting when KidNet is bothered by an external stressor of low intensity. Initially, KidNet responds with increasingly intense distress behaviour, but MomNet easily succeeds in calming down KidNet. As in this simulation the external stressor remains active, KidNet starts displaying distress behaviour again, which again activates MomNet.

The lower panel of Figure 2 depicts the same dyad with a high-intensity external stressor. Under these conditions, MomNet is not successful in calming down KidNet, though by responding at maximum intensity she does succeed in preventing KidNet from displaying the highest possible distress level. This results in a stable pattern, in which KidNet continuously emits distress responses of a moderately high intensity.

In order to depict the effects of increasing stressor intensity, it would be neither practical, nor very enlightening, to present interaction sequences like those depicted in Figure 2 for all levels of stressor intensity. How stressor intensity affects the responses of a particular KidNet–MomNet dyad can be depicted more efficiently by constructing diagrams in which all responses of either Kid or Mom during a particular range of interaction sequences are plotted against stressor intensity. In Figure 3, such diagrams are presented for the responses of the KidNet (upper panel) and the MomNet (lower panel) of the dyad that was also depicted in Figure 2. When stressor intensity was low, the responses of both networks during the first few iterations were not yet fully affected by each other's behaviour. As the inclusion of these responses would make the diagrams less clear, they include only the responses from the 20th iteration and a stressor intensity of 0.1 onwards in Figure 3.

 

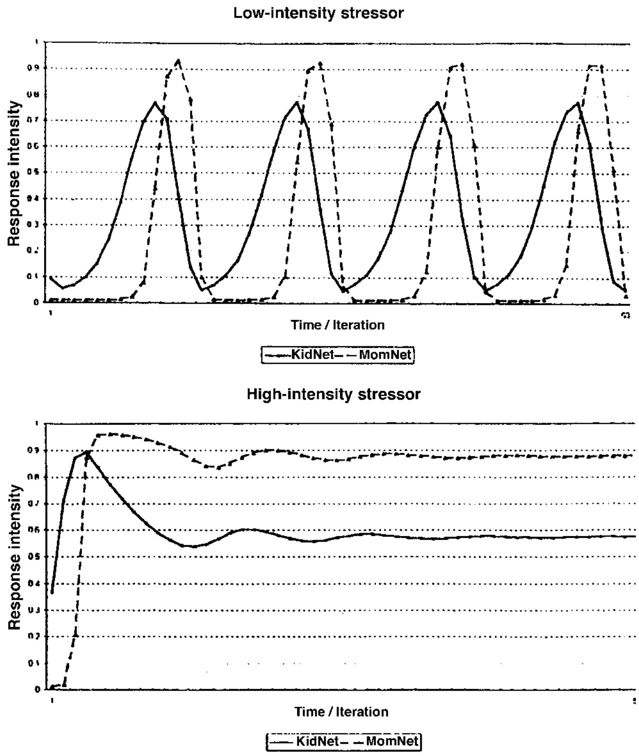


Figure 2. The intensity of a moderately irritable KidNet's distress responses (solid lines) and a moderately responsive MomNet's caring responses (broken lines), under conditions of low and high stressor intensity.

As can be seen in Figure 3 (upper panel), under conditions of low stressor intensity KidNet emits both high and low-intensity distress responses, the latter being a result of MomNet's high-intensity caring responses. Initially, increasing stressor intensity hardly affects the way this dyad interacts, be it that the lowest possible level of KidNet's responses slowly increases to slightly higher levels. When stressor intensity ranges from medium to high, it can be seen that a non-linear function governs this change in the lowest possible level of KidNet's responses. When stressor intensity becomes extremely high, the interaction becomes qualitatively different in character. MomNet now continuously emits responses of the highest possible intensity, to which KidNet responds by continuously emitting distress responses of a moderately high intensity. Note, however, that even when stressor intensity is extreme, KidNet's responses do not quite reach the highest possible intensity, as a result of MomNet's continuous high-intensity caring behaviour.

Two-dimensional diagrams like those in Figure 3 are commonly used to depict responses of a non-linear dynamic system to parameter changes, but for the present purposes, it is a disadvantage that the data have been blotted out across the time/iteration dimension. Therefore, the main results will be presented using three-dimensional diagrams, which allow depicting both the stressor-intensity, and the time/iteration dimensions.

 

Because of space considerations, only a small, yet representative, portion of the results will be presented in this paper. As the results for both types of external stressors were qualitatively similar, we decided to focus on the results obtained for one stressor. Furthermore, because varying MomNet's sensitive responsiveness and varying KidNet's irritability also had qualitatively similar effects on the way increasing distress affected the nature of the interaction, we decided to focus on the variable that has attracted most attention from empirical researchers, i.e. the mother's sensitive responsiveness. For this purpose, data will be presented from a series of eight dyads that all consist of the same moderately irritable KidNet and one of the eight differentially responsive MomNets. We will further restrict the presentation of results to KidNet's responses. These are the most interesting, because they reflect KidNet's response to both the external stressor and MomNet's caring behaviour.

Graphical representations of the intensity of KidNet's distress response during the interaction, as a function of increasing stressor intensity, are presented in Figure 4. In these graphs, the vertical Y-axis represents the intensity of KidNet's distress response, the X-axis the time or iteration dimension, and the Z-axis the stressor intensity dimension.

The upper left graph of Figure 4 depicts KidNet interacting with an extremely responsive MomNet. As is evident, the effect of increasing distress is largely that KidNet takes less time before emitting its first distress response, and that

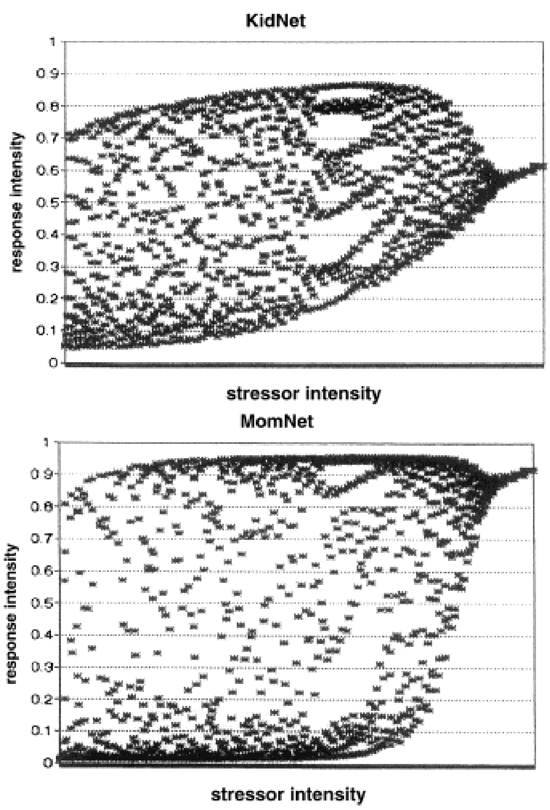


Figure 3. Diagrams representing a moderately irritable KidNet's distress responses and a moderately responsive MomNet's caring responses as a function or stressor intensity.

 

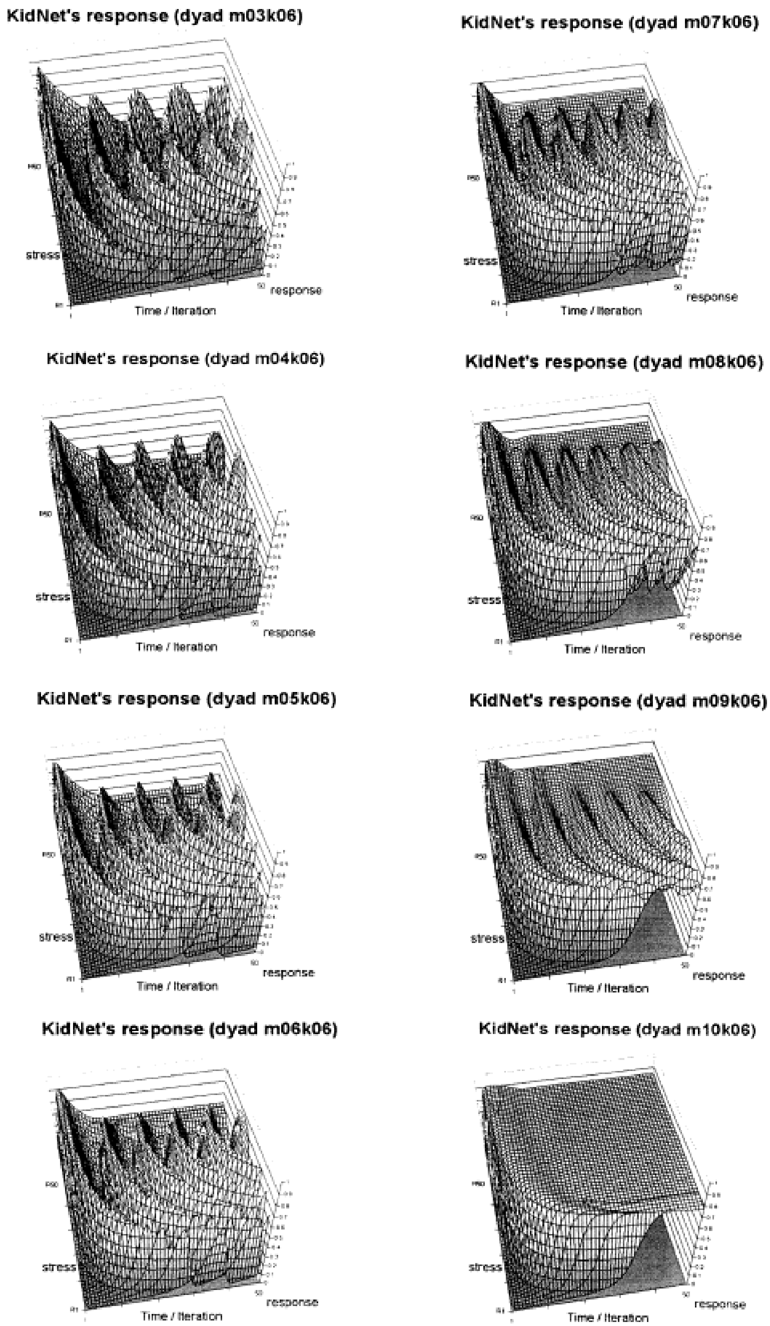


Figure 4. The intensity of a moderately irritable KidNet's distress as a function of time and stressor intensity, and when interacting with eight differentially responsive MomNets. MomNet's sensitive responsiveness varies from high (0.3) to low (1.0).

 

these responses become more intense with increasing stressor intensity. It can also be seen, however, that KidNet is always calmed down by MomNet, no matter what level of stressor intensity.

The upper left graph of Figure 4 also reveals a paradoxical phenomenon that can be seen even more clearly in the graphs depicting KidNet's interaction with slightly less responsive MomNets. Particularly when stressor intensity is at its most extreme, KidNet unsurprisingly emits an extremely intense initial distress response. Surprisingly, however, this initial high-intensity response soon reverts to a less intense and stable distress response, despite the high-intensity external stressor. An examination of MomNet's responses (not depicted here) revealed that KidNet's initial distress response stimulates the responsive MomNets to emit extremely intense and continuous caring responses, which subsequently keep KidNet at a stable and relatively low level of distress.

Except for the dyad with the extremely unresponsive MomNet (see the lower right-hand graph of Figure 4), all graphs essentially show the two interaction patterns discussed above. At low-to-intermediate levels of stressor intensity, an oscillating pattern represents MomNet's successful attempt to calm down KidNet, even though KidNet's calming down in response to MomNet's intervention becomes somewhat delayed when interacting with the less responsive MomNets. At high levels of stressor intensity, KidNet emits a stable pattern of distress responses, as a result of MomNet's continuous emission of high-intensity caring responses. However, as can be seen in the graphs in the right-hand column of Figure 4, the latter pattern stabilizes at an ever-higher intensity level in the interactions with the less responsive MomNets. Finally, when interacting with the least responsive MomNet, the stable pattern is no longer restricted to high levels of stressor intensity, but has expanded across virtually the whole stressor intensity range. This MomNet is simply too slow to be able to affect KidNet's responses at about any level of stressor intensity.

Note that a similarly paradoxical phenomenon also characterizes the interactions with the unresponsive MomNets, as described for the interactions with the responsive MomNets. For example, in the third graph of the right-hand column of Figure 4, it can be seen that KidNet is slow to build up a distress response at low levels of stressor intensity, but once this response has been built up, it remains at virtually the same level without being affected by MomNet's response. Surprisingly, however, when stressor intensity increases to an intermediate level, MomNet becomes somewhat more successful in calming down KidNet. It is as if the very slow build-up of KidNet's distress response escapes the unresponsive MomNet's attention, which results in a response that is too weak and too late to affect KidNet at all. With higher levels of stressor intensity, KidNet's response builds up more quickly, which results in activating MomNet, which again results in KidNet being soothed to some extent.

## STUDY TWO: THE LOGISTIC GROWTH MODEL

Logistic growth models can be used to model the changes over time of systems that consist of interconnected entities that are changing over time themselves. These entities are called 'growers'. The change of a grower $L$ in one time unit, from time $t$ to time $t+1$, is described by the so-called logistic growth, or Verhulst equation,

$$L_{t+1} = L_t \cdot (1 + r) - r \cdot L_t^2 / K, \qquad \text{(eq. 1)}$$

 

in which $L$ = grower at time $t$, $r$ = growth parameter, and $K$ = carrying capacity.

This equation is a basic form of a large family of equations that is well suited to describe the development of living systems, both in biology and in psychology (Van Geert, 1991). Important characteristics of the logistic growth equation are that its own previous value affects the value of a grower non-linearly, and that growth cannot continue endlessly because of the limited resources that are characteristic of all living systems (represented in the equation by $K$). A system of connected growers consists of an interconnected set of equations, each of which represents one grower. The effect of other growers on the growth of a target grower is determined non-linearly by the state of the system, that is, by the values of the affected grower, and by the values of all affecting growers.

To simulate mother–child interaction using the logistic growth approach, we will take one grower (further referred to as KidLog) to represent a child experiencing discomfort because of an external stressor, and another grower (MomLog) to represent the mother who is trying to comfort her child. The form of each equation is based on the assumptions concerning the way in which maternal and infant behaviour change as a function of each other. We made these assumptions explicit in the introductory section when describing our psychological model. The nature of the changes in the interactants' behaviour over many time units is an emergent property of the way in which the changes at the micro scale of $t$ to $t+1$ are specified in the logistic growth equations.

### *Method*

Starting from the work of Van Geert (1994), we developed a system with two equations, i.e. one for KidLog and one for MomLog[1]. As in the connectionist simulation both external stressors yielded results that were qualitatively similar, only one stressor was used in the logistic growth simulation. A classic logistic growth function describes KidLog's distress, i.e.:

$$D_{t+1} = D_t \cdot (1 + r) - r \cdot D_t^2 / K, \qquad \text{(eq. 2)}$$

in which $D_t$ = KidLog's distress response at time $t$; and other values represent those defined in Equation (1).

We assume that the intensity of KidLog's distress responses is positively affected by the intensity of the external stressor and by KidLog's irritability, and that it is negatively affected by the intensity of MomLog's caring behaviour. In principle, this effect could be reached in several ways. For example, MomLog could affect KidLog's distress by affecting its growth rate, its carrying capacity, or by directly adding an additional factor. The second and the third options both imply that MomLog can affect the resulting maximum stable value of KidLog. This seems implausible, because only short-time interactions are simulated in this study. We, therefore, used a model in which MomLog affects KidLog's growth rate, rather than its other parameters.

We further assumed that KidLog's irritability represents its sensitivity to the external stressor, rather than its sensitivity to MomLog's caring behaviour, and that there is a maximum stable value that KidLog's distress can reach. This is the value of $K$, which is set to 1 in this simulation, and so it can be left out of the equation. The equation for the growth parameter $r$ in Equation (2) is:

$$r = e \cdot i - C_t, \qquad \text{(eq. 3)}$$

with $C_t$ = MomLog's caring response at time $t$; $i$ = irritability and $e$ = the external stressor[2].

 

In a logistic growth equation, the simulation gets stuck once the value '1' or '0' is reached. As the special effect of these two numbers is only mathematical, and has no psychological meaning, this effect is prevented by including a very small random number. This random number depends on the level of the grower, to prevent differences in its relative impact. Accordingly, when combining Equations (2) and (3), we added a small random number. The resulting equation is:

$$D_{t+1} = D_t \cdot (1 + e \cdot i - C_t) - (e \cdot i - C_t) \cdot D_t^2 - D_t \cdot \text{rand}, \qquad \text{(eq. 4)}$$

with $D_t$ = KidLog's distress response at time $t$ (initial value = 0.005) and rand = a random number drawn from an equally distributed range between 0 and 0.005.

For MomLog, the same type of equation was used. As before, we chose to let KidLog affect the growth rate parameter of the MomLog equation. In addition, we had to decide whether MomLog's responses would be affected by the intensity of KidLog's distress behaviour as such, or by changes in its intensity. The equivalent empirical question is whether mothers react only to the intensity of a child's distress behaviour, or also to changes in its intensity. As no research or theory provides answers to such questions, we assumed for this study that mothers are likely to react to both types of information. Accordingly, the equation was constructed in such a way that both an increase (or decrease) in the intensity of the KidLog's behaviour, and the intensity of its behaviour, affect MomLog's growth rate parameter, and by that the intensity of MomLog's response. The resulting MomLog equation is:

$$C_{t+1} = C_t \cdot (1 + r) - r \cdot C_t^2 / K, \qquad \text{(eq. 5)}$$

with $C_t$ = MomLog's caring behaviour at time $t$, and other values equal to those already stated.

We assumed that the intensity of MomLog's caring responses is determined by: (1) the intensity of KidLog's distress response, (2) changes in the intensity of KidLog's distress response, and (3) MomLog's sensitive responsiveness. Accordingly, the growth parameter of MomLog ($r$ in Equation (5)) is a function of the intensity of KidLog's distress response ($D_t$) and of changes in this intensity ($D_t - D_{t-1}$). For the sake of simplicity, we assume that intensity and change can compensate each other, that is, they are added.

It would not make sense to add the effect of sensitive responsiveness also, because its effect should depend on the intensity of KidLog's distress responses. The factor representing KidLog's distress in the '$r$' of the MomLog equation is multiplied, therefore, by the sensitive responsiveness parameter '$s$'. Two additional parameters, $y$ and $x$, have a scaling function, i.e. '$y$' regulates the relative impact of distress intensity, as compared with the changes in that intensity, and '$x$' regulates the position of $r$ relative to 0 (negative values of $r$ result in decrease of the grower).
Accordingly,

$$r = (s \cdot (y \cdot D_t + D_t - D_{t-1}) - x). \qquad \text{(eq. 6)}$$

There is a maximum stable value that MomLog's caring behaviour can reach, that is, this behaviour has a ceiling. This is represented in the equation by the value of $K$, which was again set to 1. As before, we added a small random number. Combining Equations (5) and (6) gives:

 

$$C_{t+1} = C_t \cdot (1 + s \cdot (y \cdot D_t + D_t - D_{t-1}) - x) - (s \cdot (y \cdot D_t + D_t - D_{t-1}) - x) \cdot C_t^2 - C_t \cdot \text{rand}, \quad \text{(eq. 7)}$$

in which $C_t$ = MomLog's caring behaviour at time $t$, as stated above (initial value 0.005), as is $D_t$ = KidLog's distress at time $t$, $s$ = sensitive responsiveness parameter, $x$ = scaling parameter (0.5), $y$ = scaling parameter regulating the relative impact of $D_t$, as compared with $D_t - D_{t-1}$ (0.1) and rand = a random number drawn from an equally distributed range between 0 and 0.005, as previously outlined. In Figure 5, a graphical depiction of the full model is presented.

As was true for the connectionist network simulation, eight levels of sensitive responsiveness and eight levels of irritability were used to produce differentially responsive MomLogs and differentially irritable KidLogs. The eight levels of irritability were, in order of increasing irritability, 2.5, 3, 3.5, 4, 4.5, 5, 5.5 and 6. The eight levels of sensitive responsiveness were in order of sensitive responsiveness were 7, 8, 9, 10, 11, 12, 13 and 14[3]. By combining the resulting KidLogs and MomLogs, 64 dyads were created. For each dyad, we ran simulations for 50 different levels of stressor intensity ranging from 0.1 (low stressor intensity) to 0.3 (high stressor intensity). Each simulation started with the same low initial values for both MomLog and KidLog. The model covers 110 iterations.

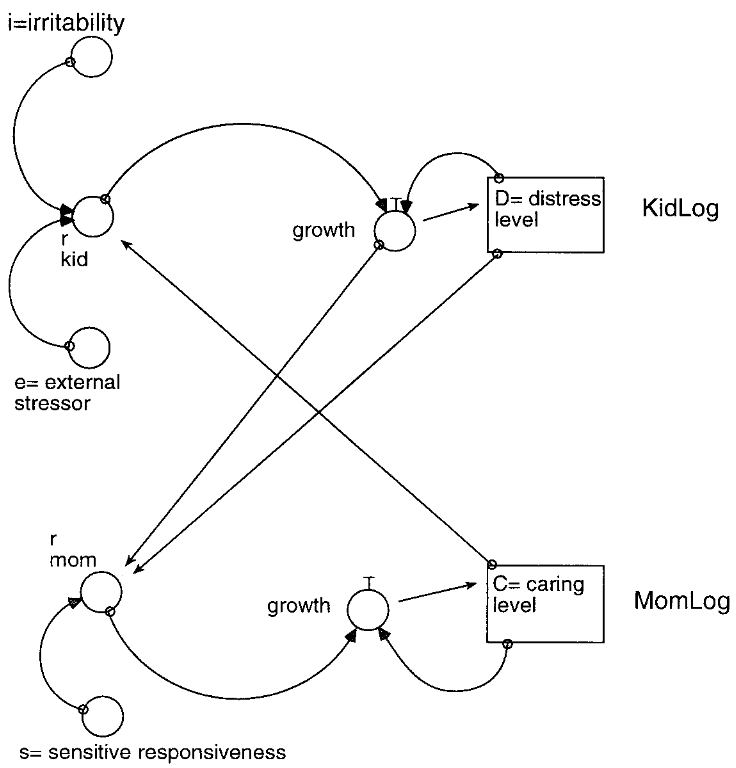


Figure 5. The logistic growth model.

### *Results and discussion*

We inspected all 64 dyads' trajectories over the whole stressor intensity range to ensure that none would yield non-interpretable results. However, to save space, the results will only be presented for the same selection of KidLog?MomLog dyads that we described for the connectionist network simulation. As before, three-dimensional graphs will be used to present the results.

In Figure 6, graphs are presented of the eight dyads in which a moderately irritable KidLog was combined with eight differentially responsive MomLogs. For the lower levels of stressor intensity, the intensity of KidLog's distress decreases, having reached an initial maximum, then it stabilizes after either one sharp dip or some small fluctuations. For these levels of stressor intensity MomLog's sensitive responsiveness affects: (1) how long it takes her to get KidLog from emitting distress responses at the highest possible intensity, and (2) the eventual level at which KidLog's distress stabilizes. The more responsive MomLog is, the shorter KidLog emits a maximum intensity distress response and the lower the eventual equilibrium level.

As can be seen in the lower right-hand graphs of Figure 6, in dyads with an unresponsive MomLog, stressor intensity has a paradoxical effect on how long KidLog emits maximum intensity distress responses before being calmed down. That is, with increasing stressor intensity, the period of maximally intense distress becomes shorter, rather than longer. The explanation for this effect is similar to the explanation given for a comparable effect in the network simulation: at extremely low levels of stressor intensity, the build-up of KidLog's response is too slow to alarm the unresponsive MomLogs and, therefore, KidLog does not calm down as quickly as when the stressor is more intense.

It should also be noted that for high levels of stressor intensity, KidLog stabilized immediately after it reached its maximum. This was true for all MomLogs, regardless of their sensitive responsiveness. Accordingly, in this simulation, levels of stressor intensity exist that cause KidLog to emit maximum intensity distress responses continuously, and even the most responsive MomLog cannot stop this.

## GENERAL DISCUSSION

The aim of the present study was to clarify the empirical implications of applying a non-linear dynamic systems perspective to mother–child interaction. To reach this aim, we presented two non-linear dynamic models of mother–child interaction.

In both types of simulations, different patterns of interaction occurred. In the first pattern, the responses of both Mom and Kid were well adjusted to each other. The intensity of Mom's caring responses increased when Kid's distress responses increased, which resulted in quietening Kid. As in our simulations, Mom's responses did not affect the external stressor, Kid soon started to emit distress responses again, which led Mom to intervene successfully again. In the network simulations, this resulted in an oscillatory pattern of both KidNet's and MomNet's responses. In the logistic simulations, the oscillations in KidLog's and MomLog's responses soon faded away to stabilize at a low level of intensity. Because both interactants reacted appropriately to each other's responses, this pattern can be labelled *effective* interaction.

 

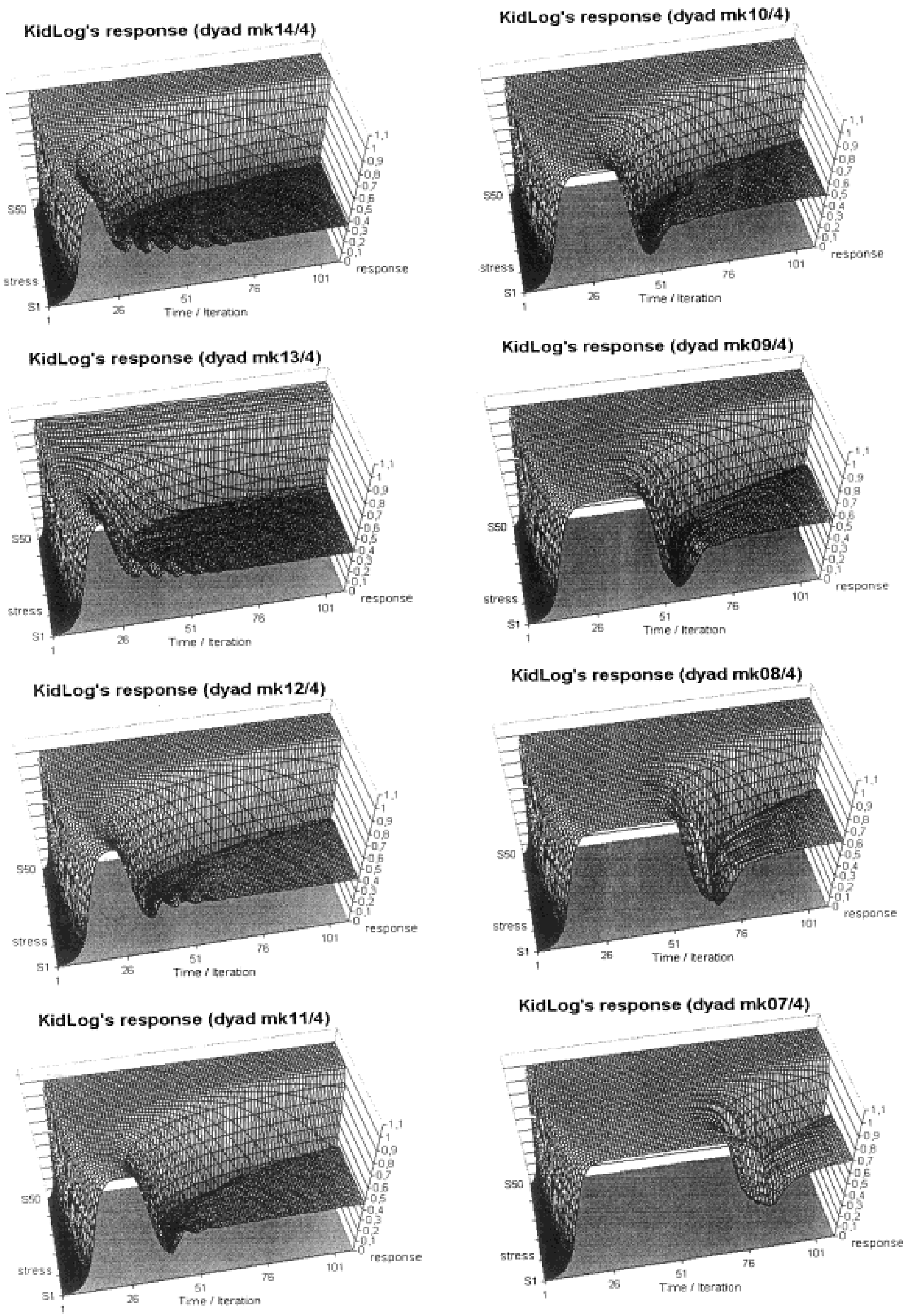


Figure 6. The intensity of a moderately irritable KidLog's distress as a function of time and stressor intensity and when interacting with eight differentially responsive MomLogs. MomLog's sensitive responsiveness varies from high (14) to low (7).

In the second interaction pattern, Kid continuously emitted high-intensity distress responses, without Mom being able to soothe her child, even though she also emitted high-intensity caring responses. This pattern can be designated *ineffective*, because both interactants were stuck and did not affect each other's responses in the appropriate way.

A third interaction pattern occurred in the network simulation in the dyads with a responsive MomNet when the intensity of the external stressor was extremely high. This pattern resembled the ineffective pattern, in that Mom continuously emitted high-intensity caring responses, but it differed from the ineffective pattern, in that Kid continuously emitted low-intensity distress responses. As in this pattern Mom had to emit high-intensity caring responses continuously to keep Kid's distress low, we will call this pattern a *desperate* interaction pattern.

Both the connectionist network, and the logistic growth simulations, were characterized by some rather abrupt changes from one interaction pattern to another pattern. This is especially clear when looking at how the continuous increase in stressor intensity affected the nature of the interaction. For example, in the network simulation, no large changes in stressor intensity were needed to produce a change from effective to either desperate (in the dyads with a responsive Mom) or ineffective (in the dyads with an unresponsive Mom) interaction. The same was true for the change from effective to ineffective interaction in the logistic growth simulation. Accordingly, these simulations show sharp thresholds for stressor intensity. When stressor intensity was below this threshold, an effective interaction pattern emerged, but when it was above this threshold, the emerging pattern was either ineffective, or desperate.

As is clear from the left column of Figure 6, the logistic growth dyads with a responsive MomLog interacted effectively at low levels of stressor intensity, but ineffectively at high levels of stressor intensity. The same was true for at least some of the network dyads (e.g. m07k06 and m08k06, see Figure 4). Thus, the above findings confirm our predictions that both models would produce dyads in which Mom's interventions affect Kid's distress responses at low levels of stressor intensity, but not at high levels of stressor intensity, and that the change between both regimes would be non-linear.

Because we varied Mom's sensitive responsiveness and Kid's irritability in only eight steps, it is difficult to say whether changes along these dimensions had similarly abrupt effects. Inspection of Figures 4 and 6 suggests, however, that changes in Mom's sensitive responsiveness of a similarly large magnitude had very different effects, depending on the state of the system. For example, in the neural network simulations, small differences in Mom's sensitive responsiveness did not affect the nature of the interaction very much if responsiveness was medium to high (see the left-hand column of Figure 4). However, when responsiveness was low, differences of a similar size had a much stronger effect on the nature of the interaction (see the right-hand column of Figure 4).

Similarly, decreasing the most responsive MomLog's responsiveness in the logistic growth simulation had only minor effects on how long KidLog emitted maximum intensity distress responses at low values of stressor intensity (see the left-hand column of Figure 6). However, decreasing the moderately responsive MomLog's responsiveness to a similar degree had much stronger effects on how long KidNet emitted maximum intensity distress responses at low values of stressor intensity (see the right-hand column of Figure 6).

Our findings imply that empirical researchers who want to take seriously the idea that an interacting mother–child dyad constitutes a non-linear dynamic system, could start by looking for critical thresholds. Such thresholds might exist both for the intensity of external stressors, and for relevant characteristics of both mother and child. To our knowledge, no formal empirical studies show the existence of this type of non-linear phenomena in actual mother?child interaction. The results of our simulations, however, are reminiscent of the concept of 'good-enough' mothering, as it was used by Winnicott (1988). According to Winnicott, a mother does not have to be perfect. A moderate quality of mothering is usually sufficient for a positive development of the child. However, if the quality is below a specific threshold, we can expect the child's development to suffer.

Our simulations also imply, however, that any such thresholds are likely to be unique for each particular mother–child dyad. They depend on the dynamic history of the dyad, and on characteristics of both the child and the mother. Accordingly, to identify them, we require an analysis of the interactive process (Fogel, 1982).

An empirical demonstration of the existence of critical thresholds would have important practical implications also. For example, in dyads that are near such a threshold, even a slight improvement of the external circumstances, or a training programme producing a slight improvement in the mother's sensitive responsiveness, could matter a lot with regard to the quality of the interaction. In other dyads, however, even much larger changes in these factors would have hardly any effect at all. In such cases, it would obviously make little sense to try to change them.

In the 'Results and discussion' sections of both studies, we described two examples of what we called paradoxical or counterintuitive effects of increasing stressor intensity. The first concerned the occurrence of the 'desperate' interaction pattern in the network simulation, in which KidNet's continuous low-intensity distress responses coincide with MomNet's high-intensity caring responses. The obvious psychological interpretation is that of a mother who is shocked by the intensity of her child's distress responses and who, therefore, uses all available means to alleviate the child's suffering, with the paradoxical effect that the child is better soothed than when its initial distress response would have been less intense. The second example concerned an effect found in both simulations at low stressor intensities, i.e. that the build-up of KidNet's distress was only sufficient to activate an unresponsive MomNet when stressor intensity was above a certain minimum. The corresponding psychological interpretation would be that an unresponsive mother tends to virtually ignore her child's low-intensity distress responses, while she pays some attention to medium-intensity distress responses. As a result, her child experiences more distress in relatively harmless situations than in more serious situations.

In our view, both examples illustrate the type of effects that are to be expected when the theoretical considerations that we discussed in the introductory section are valid. It should be noted that our point is not that the particular paradoxical effects that we described actually exist in mother–child interaction. Our point is that effects that are as paradoxical as the ones that we simulated, are to be expected if the general claim that we can see a mother–child dyad as a non-linear dynamic system is valid. In a recent paper, Haviland *et al*. (in press) discussed the same type of paradoxical effect in the field of emotion research. They argued that conceptualizing the emotional system as a non-linear dynamic system could explain such effects, which is, of course, in line with our analysis. Careful empirical research is needed to determine whether similar effects also exist in the field of mother–child interaction.

 

Our focus on those aspects of the results that were common to both models implies that we cannot say much about the differences between the results that both models generated. Some of these may have been caused by decisions that we made when constructing each model, other differences might be a result of characteristics that are inherent to either the network or the logistic growth approach, but it would require a research programme of its own to sort this out. Obviously, such a research programme should also include empirical research to enable us to decide what differences are psychologically meaningful and what are not.

Of course, the validity of any conclusion based on our work depends on the quality of the simulations. Two general kinds of criticisms could be levelled against our approach. The first is that our models are arbitrary and the second is that they are incomplete. Consequently, we will discuss both types of criticism.

We could be accused of making arbitrary decisions regarding the way we constructed each model and the choice of specific parameter settings. It is obviously true that the results generated by each model depend on choices that we made when constructing the models. For example, when constructing the logistic growth model, we decided to let MomLog's caring response affect the growth rate of the KidLog equation, rather than its carrying capacity or KidLog's level of distress. As discussed above, we had good reasons for making this choice, but we also admit that it was to some extent arbitrary. We think, however, that the need to make such choices reflects an advantage, rather than a disadvantage of the modelling approach. When constructing a model, one has to ask questions that are much more specific than is usual in the field at hand, and these questions often reveal a lack of specification in existing theories. Accordingly, the need to ask such questions helps to make clear what we know and what we do not know yet.

Another type of choice that had to be made when constructing the models concerned the parameter settings. A common objection against the type of models that we used is that one can generate any desired pattern of results by choosing the right parameter values. With respect to the construction of the network models, it should be noted that the training parameters were set to values that are commonly used with these types of networks. Decisions about how long to pursue the training were only guided by the wish to obtain networks that would roughly behave in the intended way. If we were to have made other decisions, the training procedure would certainly have generated a different set of MomNets and KidNets, which would have interacted in different ways also. There is no reason, however, to assume that this interaction would have lacked the general characteristics that we described above.

With respect to the logistic growth model, it should be noted that because of the arbitrary nature of the scales that we used for the parameters, it was not clear *a priori* what parameter ranges would yield useful results. Therefore, we had to explore parameter ranges in order to select a range resulting in behaviour that might emerge in the system to be modelled. For the psychologically meaningful parameters, i.e. sensitive responsiveness and irritability, this search resulted in the ranges that were used when varying these parameters in our simulations. For the scaling parameters $x$ and $y$, the search resulted in small ranges around the settings that we used. Within these ranges, the model only showed minor variations in behaviour. A slight change in the settings of these parameters would imply that the curves would become steeper, or that they would fluctuate somewhat more or less, or that the possible ranges for the other parameters would change to some extent. However, as was true for the network simulation, there is no reason to assume that the interaction between KidLog and MomLog would have lacked the general characteristics described above.

A second general type of criticism that could be levelled against our models, is that they are incomplete and, therefore, unrealistic. This is obviously true, as is testified, for example, by the fact that in our current models both Kid's distress and Mom's caring responses will go on infinitely. To remedy this, mechanisms of exhaustion should be incorporated into our models. For the sake of simplicity, we did not do this in the present study, but see Van Geert (1994) for a description of how this could be done for the logistic growth model.

Another way to elaborate the models presented in this paper would be to integrate them into long-term developmental models that help explain the relation between interaction patterns in early childhood, and patterns much later in life. This implies that the simulated interactions of our models should affect processes in a broader developmental model that describes changes in mothers' sensitive responsiveness and children's irritability. One could, for example, assume that an accumulation of ineffective interactions causes the mother to lose heart and to stop paying attention to her child, which implies that her sensitive responsiveness decreases. A layered model could represent such theoretical assumptions concerning development and change of both irritability and sensitive responsiveness.

For the connectionist network approach, incorporating such effects could imply that the network's ability to learn would not only be used to construct networks with particular characteristics, as in the present study. Rather, simulations should be set up so that the interacting networks provide each other's learning environment, while simultaneously interacting with each other. In this way, long-term developmental change could be made dependent on the dyad's interaction history.

Both such elaborated models, and models of the type that we described in this paper, should be tested against densely measured longitudinal data of the interactional process between real-life mothers and real-life children. Our present results suggest the kind of effect that can be expected, and it is our hope that empirical researchers will start looking for them. Such studies are likely to deepen our understanding of the interactional process, and its determinants, to a level that is unattainable when using currently available models and data.

## ACKNOWLEDGEMENTS

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## APPENDIX A TECHNICAL DETAILS OF THE NETWORK SIMULATION

The following account of how KidNet and MomNet were constructed is aimed at enabling readers who are basically familiar with the conventions regulating the use of McClelland and Rumelhart's BP programme to replicate our findings. Readers unfamiliar with BP are advised to consult the relevant parts of McClelland and Rumelhart (1988).

 

Table A1

```
definitions:
nunits 18
ninputs 10
noutputs 4
end
network:
%r 10 2  0 6
%r 12 2  6 4
%r 14 2 10 2
%r 16 2 12 2
end
biases:
%r 10 8
end
```

Although functionally separate, the KidNet and MomNet networks consisted of two parts of a single network when seen from the perspective of the simulation programme. The network as a whole was wired up so that the KidNet and MomNet parts could be trained separately, but they could also be connected to each other when simulating interaction. Following the conventions of the BP programme (McClelland and Rumelhart, 1988), the following NET file was used (see Table A1).

The first and third lines of the 'network' section of this file specify the KidNet part of the network and the second and fourth lines specify the MomNet part of the network.

When training KidNet and MomNet, we ran the BP programme with the following settings: mode 1grain = pattern, learning rate = 0.1, momentum = 0.3, and mu = 0. These parameter settings were identical to those used in an exercise with a similar recurrent network that was part of the 1993 Oxford Connectionist Models Summer School (Plunkett, 1993), and they are quite common in simulations with this type of network.

When training the KidNet or MomNet parts of the network, only the units belonging to that particular part were used. For instance, when training the KidNet part, the MomNet part of the network received no input, its output units received no feedback, and its context units were not connected to the hidden units.

## APPENDIX B CONSTRUCTING THE KIDNETS

The KidNet part of the network was first trained to activate the first or the second output unit, in response to activation of the first or the second stress-sensitive input unit, respectively. In addition, KidNet was trained to intensify its reaction the longer its input unit was activated. This was done by training the network with two sequences of five identical patterns, in which one of the stress-sensitive input units was to some extent activated. The criterion response for the corresponding output units was increased with steps of 0.2 each time an input pattern was repeated. Eight differentially irritable KidNets were constructed by varying the activation of the stress-sensitive input unit from low (0.3) to high (1.0). The lower the activation of the external input unit in the training phase, the more 'irritable' the resulting KidNet would become. The following part of the pattern file that was used to construct the most irritable KidNet represents this part of the training (see Table A2).

 

Table A2

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| k0l–1000a0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | −1 | −1 |
| k02–1000b0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.4 | 0 | −1 | −1 |
| k03–1000c0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.6 | 0 | −1 | −1 |
| k04–1000d0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.8 | 0 | −1 | −1 |
| k05–1000e0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 1 | 0 | −1 | −1 |
| k06–0100a0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | −1 | −1 |
| k07–0100b0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.4 | −1 | −1 |
| k08–0100c0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.6 | −1 | −1 |
| k09–0100d0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.8 | −1 | −1 |
| k10–0100e0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 1 | −1 | −1 |

Apart from training KidNets to intensify their responses the longer their stress-sensitive input unit was activated, they were also trained to decrease the intensity of their responses when activation of the stress-sensitive input unit was accompanied by a particular type of response from MomNet. It was arbitrarily determined that MomNet should activate the first of KidNet's social input units to affect any KidNet responses that were a result of activation of KidNet's first stress-sensitive input unit, and that MomNet should activate the second of KidNet's social input units to affect responses caused by activation of KidNet's second stress-sensitive unit. This was done by adding sequences to the training file, in which patterns activating one of the stress-sensitive input units were followed by patterns in which that same type of activation was accompanied by activation of the 'correct' type of social input unit. With each repetition of a pattern within a sequence in which activation of a particular stress-sensitive input unit was accompanied by activation of the corresponding social input unit, the criterion was lowered by steps of 0.2. In all cases, the activation of the social input units was set to 1. Accordingly, all KidNets were made equally sensitive to activation of their social input units. The following part of the pattern file that was used to construct the most irritable KidNet represents this part of the training (see Table A3).

In the final part of KidNet's training, KidNet was taught not to diminish its distress response when MomNet would respond to its distress by activating KidNet's 'wrong' social input unit. This was done by adding two sequences, in which KidNet was taught to respond with an increasingly strong distress response if activation of one of its stress-sensitive input units was accompanied by activation of the 'wrong' social input unit. The following part of the pattern file represents this part of the training (see Table A4).

KidNets were trained during 1000 epochs. This appeared to be enough to ensure that they responded roughly in the way that was intended. That is, they increased the intensity of their responses the longer their stress-sensitive input units were activated, and they decreased the intensity of their responses as soon as MomNet started to activate the appropriate social input unit.

## APPENDIX C CONSTRUCTING THE MOMNETS

MomNets were trained to activate either the first or the second output unit, in response to activation of the corresponding social input units. As with KidNets, sequences of two to five identical input patterns were used. With each repetition of the same pattern within a sequence, the criterion was increased with steps of

Table A3

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| k11-1010a0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | −1 | −1 |
| k12-1010b1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0 | −1 | −1 |
| k13-0101a0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | −1 | −1 |
| k14-010lb1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0 | −1 | −1 |
| k15-1010a0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | −1 | −1 |
| k16-1010b0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.4 | 0 | −1 | −1 |
| kl7-1010c1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.2 | 0 | −1 | −1 |
| kl8-1010d1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0 | −1 | −1 |
| kl9-010la0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | −1 | −1 |
| k20-010lb0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.4 | −1 | −1 |
| k21-010lc1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.2 | −1 | −1 |
| k22-010ld1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0 | −1 | −1 |
| k23-0010a0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | −1 | −1 |
| k24-0010b0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.4 | 0 | −1 | −1 |
| k25-0010c0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.6 | 0 | −1 | −1 |
| k26-0010d1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.4 | 0 | −1 | −1 |
| k27-0010e1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.2 | 0 | −1 | −1 |
| k28-0010f1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0 | −1 | −1 |
| k29-010la0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | −1 | −1 |
| k30-010lb0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.4 | −1 | −1 |
| k31-010lc0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.6 | −1 | −1 |
| k32-0101d1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.4 | −1 | −1 |
| k33-010le1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.2 | −1 | −1 |
| k34-0101f1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0 | −1 | −1 |
| k35-1010a0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | −1 | −1 |
| k36-1010b0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.4 | 0 | −1 | −1 |
| k37-1010c0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.6 | 0 | −1 | −1 |
| k38-1010d0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.8 | 0 | −1 | −1 |
| k39-1010e1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.6 | 0 | −1 | −1 |
| k40-1010f1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.4 | 0 | −1 | −1 |
| k41-1010g1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.2 | 0 | −1 | −1 |
| k42-1010h1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0 | −1 | −1 |
| k43-0101a0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | −1 | −1 |
| k44-0101b0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.4 | −1 | −1 |
| k45-0101c0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.6 | −1 | −1 |
| k46-010ld0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.8 | −1 | −1 |
| k47-010le1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.6 | −1 | −1 |
| k48-010lf1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.4 | −1 | −1 |
| k49-010lg1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.2 | −1 | −1 |
| k50-010lb1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0 | −1 | −1 |
| k51-1010a0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | −1 | −1 |
| k52-1010b0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.4 | 0 | −1 | −1 |
| k53-1010c0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.6 | 0 | −1 | −1 |
| k54-1010d0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.8 | 0 | −1 | −1 |
| k55-1010d0 | 0.3 | 0 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 1 | 0 | −1 | −1 |
| k56-1010e1 | 0.3 | 1 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.8 | 0 | −1 | −1 |
| k57-1010f1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.6 | 0 | −1 | −1 |
| k58-1010g1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.4 | 0 | −1 | −1 |
| k59-1010h1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0.2 | 0 | −1 | −1 |
| k60-1010i1 | 0.3 | 0 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0 | −1 | −1 |
| k61-010la0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | −1 | −1 |
| k62-010lb0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.4 | −1 | −1 |
| k63-0101c0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.6 | −1 | −1 |
| k64-010ld0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.8 | −1 | −1 |
| k65-010le0 | 0 | 0.3 | 0 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 1 | −1 | −1 |
| k66-010lf1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.8 | −1 | −1 |
| k67-010lg1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.6 | −1 | −1 |
| k68-010lh1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.4 | −1 | −1 |
| k69-010li1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.2 | −1 | −1 |
| k70-010lj1 | 0 | 0.3 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0 | −1 | −1 |

 

Table A4

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| k71-1001a0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | 0 | −1 | −1 |
| k72-1001b2 | 0.3 | 0 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0.4 | 0 | −1 | −1 |
| k73-1001c2 | 0.3 | 0 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0.6 | 0 | −1 | −1 |
| k74-1001d2 | 0.3 | 0 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 0.8 | 0 | −1 | −1 |
| k75-1001e2 | 0.3 | 0 | 0 | 1 | −10 | −11 | 0 | 0 | 0 | 0 | 1 | 0 | −1 | −1 |
| k76-0110a0 | 0 | 0.3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.2 | −1 | −1 |
| k77-0110b2 | 0 | 0.3 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.4 | −1 | −1 |
| k78-0110c2 | 0 | 0.3 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.6 | −1 | −1 |
| k79-0110d2 | 0 | 0.3 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 0.8 | −1 | −1 |
| k80-0110e2 | 0 | 0.3 | 1 | 0 | −10 | −11 | 0 | 0 | 0 | 0 | 0 | 1 | −1 | −1 |

0.2. Differentially responsive MomNets were produced by varying the level of activation of the social input units from 0.3 to 1.0. The lower these values, the more responsive the resulting MomNets would become. To ensure that MomNets would stop responding when their social input units would not be activated, all training sequences ended with a pattern in which none of the input units was activated, and in which the criterion was set to 0. The following pattern file was used to construct a moderately sensitive MomNet (see Table A5).

The MomNets were trained during 2000 epochs. This appeared to be enough to ensure that MomNets increased the intensity of their responses the longer a particular social input unit was activated, and that they stopped responding when the input units were no longer activated.

## APPENDIX D CONSTRUCTING KIDNET–MOMNET DYADS

In all, 64 KidNet–MomNet dyads were constructed by coupling each KidNet to each of the MomNets. This was done by integrating the relevant weights from the previously trained KidNet and MomNet parts of the network into one single weight file representing the network for a dyad. For instance, to construct a dyad consisting of the extremely irritable KidNet, and the moderately sensitive MomNet, that resulted from training the network with the files described above, we first extracted the weights of the KidNet part of the network from the weights file resulting from training the KidNet part of network. Second, we extracted the weights of the MomNet part of the network from the weights file resulting from training the MomNet part of the network. Finally, the extracted KidNet and MomNet weights were integrated into a new weights file, representing this particular KidNet–MomNet dyad. To study the interaction of KidNet and MomNet within a particular dyad, the weight file of the dyad was loaded into BP, and the network was subsequently tested with all of 50 test files. Each test file consisted of a single sequence of 50 identical patterns that activated either the first or the second stress-sensitive input unit of KidNet. The test files were constructed such that both KidNet's and MomNet's context units were in use, that is, both networks functioned as recurrent networks of the type used by Jordan (1986) and Elman (1990). In addition, KidNet's output units were now connected to MomNet's social input units, and MomNet's output units were now connected to KidNet's social input units. The 50 test files differed in terms of the extent to which KidNet's stress-sensitive input unit was activated. Activation levels varied from 0.02 (which is extremely low, given the

 

Table A5

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| m01-0600a | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | 0 | 0 | −1 | −1 | 0.2 | 0 |
| m02-0600b | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | −12 | −13 | −1 | −1 | 0.4 | 0 |
| m03-0600c | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | −12 | −13 | −1 | −1 | 0.6 | 0 |
| m04-0600d | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | −12 | −13 | −1 | −1 | 0.8 | 0 |
| m06-0600e | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | −12 | −13 | −1 | −1 | 1 | 0 |
| m06-0600e | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | −12 | −13 | −1 | −1 | 0 | 0 |
| m06-0006a | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | 0 | −1 | −1 | 0 | 0.2 |
| m07-0006b | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | −12 | −13 | −1 | −1 | 0 | 0.4 |
| m08-0006c | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | −12 | −13 | −1 | −1 | 0 | 0.6 |
| m09-0006d | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | −12 | −13 | −1 | −1 | 0 | 0.8 |
| m10-0006e | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | −12 | −13 | −1 | −1 | 0 | 1 |
| m10-0006e | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | −12 | −13 | −1 | −1 | 0 | 0 |
| m0l-0600a | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | 0 | 0 | −1 | −1 | 0.2 | 0 |
| m02-0600b | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | −12 | −13 | −1 | −1 | 0.4 | 0 |
| m03-0600c | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | −12 | −13 | −1 | −1 | 0.6 | 0 |
| m04-0600d | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | −12 | −13 | −1 | −1 | 0.8 | 0 |
| m06-0600e | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | −12 | −13 | −1 | −1 | 0 | 0 |
| m06-0006a | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | 0 | −1 | −1 | 0 | 0.2 |
| m07-0006b | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | −12 | −13 | −1 | −1 | 0 | 0.4 |
| m08-0006c | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | −12 | −13 | −1 | −1 | 0 | 0.6 |
| m09-0006d | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | −12 | −13 | −1 | −1 | 0 | 0.8 |
| m10-0006e | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | −12 | −13 | −1 | −1 | 0 | 0 |
| m0l-0600a | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | 0 | 0 | −1 | −1 | 0.2 | 0 |
| m02-0600b | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | −12 | −13 | −1 | −1 | 0.4 | 0 |
| m03-0600c | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | −12 | −13 | −1 | −1 | 0.6 | 0 |
| m06-0600e | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | −12 | −13 | −1 | −1 | 0 | 0 |
| m06-0006a | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | 0 | −1 | −1 | 0 | 0.2 |
| m07-0006b | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | −12 | −13 | −1 | −1 | 0 | 0.4 |
| m08-0006c | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | −12 | −13 | −1 | −1 | 0 | 0.6 |
| m10-0006e | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | −12 | −13 | −1 | −1 | 0 | 0 |
| m0l-0600a | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | 0 | 0 | −1 | −1 | 0.2 | 0 |
| m02-0600b | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | −12 | −13 | −1 | −1 | 0.4 | 0 |
| m06-0600e | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | −12 | −13 | −1 | −1 | 0 | 0 |
| m06-0006a | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | 0 | 0 | −1 | −1 | 0 | 0.2 |
| m07-0006b | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.6 | −12 | −13 | −1 | −1 | 0 | 0.4 |
| m10-0006e | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | −12 | −13 | −1 | −1 | 0 | 0 |

fact that even the most irritable KidNet was constructed using an activation level of 0.3) to 1.00 (which equals the activation level that was used when constructing the least irritable KidNet). A part of the test file that activated KidNet's second stress-sensitive input unit with the medium intensity of 0.52 is shown in Table A6.

Table A6

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| "ts052x" | 0 | 0.52 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| "ts052x" | 0 | 0.52 | −16 | −17 | −10 | −11 | −14 | −15 | −12 | −13 | 0 | 0 | 0 | 0 |
| "ts052x" | 0 | 0.52 | −16 | −17 | −10 | −11 | −14 | −15 | −12 | −13 | 0 | 0 | 0 | 0 |
| "ts052x" | 0 | 0.52 | −16 | −17 | −10 | −11 | −14 | −15 | −12 | −13 | 0 | 0 | 0 | 0 |
| "ts052x" | 0 | 0.52 | −16 | −17 | −10 | −11 | −14 | −15 | −12 | −13 | 0 | 0 | 0 | 0 |
| "ts052x" | 0 | 0.52 | −16 | −17 | −10 | −11 | −14 | −15 | −12 | −13 | 0 | 0 | 0 | 0 |
| "ts052x" | 0 | 0.52 | −16 | −17 | −10 | −11 | −14 | −15 | −12 | −13 | 0 | 0 | 0 | 0 |
| "ts052x" | 0 | 0.52 | −16 | −17 | −10 | −11 | −14 | −15 | −12 | −13 | 0 | 0 | 0 | 0 |
| "ts052x" | 0 | 0.52 | −16 | −17 | −10 | −11 | −14 | −15 | −12 | −13 | 0 | 0 | 0 | 0 |
| "ts052x" | 0 | 0.52 | −16 | −17 | −10 | −11 | −14 | −15 | −12 | −13 | 0 | 0 | 0 | 0 |

***Notes***

1. The model is easy to reproduce in a spreadsheet programme. All necessary information is included in the text, in addition an EXCEL file with the model will be sent by e-mail on request. In line with Van Geert's work (Van Geert, 1994), we used difference equations in this model, rather than differential equations. Even though the variables that are used in this model are continuous, we preferred to use difference equations, because this makes the model simple and easy to reproduce for anyone with a spreadsheet programme. However, we also constructed a version of the model using a differential equations approach. The results using the latter model would not lead to different conclusions as those stated in the text based on the difference equations model. A STELLA file with the differential equations model will be sent by e-mail on request.
2. The external stressor and KidLog's irritability compensate for each other. In a strict mathematical sense, one single parameter could replace them. However, because of the restricted parameter ranges and the psychological meaning of the parameters, we kept them as two separate parameters.
3. These values are arbitrarily chosen. Just as one could as well assign intelligence scores using a scale ranging from 0 to 10, as a scale ranging from 50 to 150, we could have used any other range here.

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